LESSONS LEARNED AND FINAL REPORT FOR HOUDINI® VEHICLE REMOTE OPERATIONS AT OAK RIDGE NATIONAL LABORATORY

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ABSTRACT

In 1996 the first hydraulically powered, remotely operated, track driven vehicle, commonly know as Houdini®, arrived at the U.S. Department of Energy - Oak Ridge National Laboratory (ORNL). This system supported radioactive waste retrieval for the Gunite Tanks Remediation Project. The Houdini®-I system underwent cold testing at the Robotics and Process Systems Division's Tanks Technology Cold Test Facility at ORNL. The cold tests allowed the full integration of the Houdini®-I system with other remotely operated equipment to complete the Radioactive Tank Cleaning System for the Gunite Tanks Remediation Project.

In July 1997 the Houdini®-I remotely operated vehicle was deployed, and over the next 8 months the Houdini®-I was operated inside two 25-ft diameter tanks in the North Tank Farm and one 50-ft diameter tank at the South Tank Farm at ORNL in a harsh chemical and radiological environment. The system successfully accomplished a variety of tasks that were important for successful waste retrieval, completing the "hot tests" conducted as part of a Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) Treatability Study. During hot tests, many valuable lessons were learned, which were documented, and later communicated back to RedZone Robotics Inc., the manufacturer of the Houdini® I system. A second system, Houdini®-II, was in its design stage during the hot tests. Lessons-learned on the Houdini®-I drove the design and specifications for the second-generation Houdini®-II system. Improvements were targeted at two main areas, reliability and maintenance. These improvements were implemented in order to meet As Low As Reasonably Achievable (ALARA) exposure principle requirements, and further improve the Houdini® system for use in higher radiation environments. The main redesign focused on improving the ergonomics on the Tether Management And Deployment System and modifying many of the electrical and plumbing features of the vehicle.

The Houdini®-II system arrived at ORNL in September 1998 for cold testing before its deployment in the larger gunite tanks in the ORNL South Tank Farm. In January 1999 the vehicle was deployed into tank W-7 under the Bechtel Jacobs Company LLC contract. The Houdini® -II system successfully completed waste retrieval operations in tanks W-7, W-8, W-9, and W-10. The Houdini®-II system required less maintenance than the original Houdini®-I prototype. It proved reliable during waste retrieval operations, helping to speed up the process, and its versatility proved valuable in completing the Gunite Tanks Remediation Project ahead of schedule.

INTRODUCTION

The U.S. Department of Energy (DOE) is cleaning up and closing approximately 300 underground tanks that store radioactive and hazardous waste remaining from the Cold War and research and development activities at DOE sites around the country. These tanks contain millions of gallons of low- and high-level radioactive mixed waste and come in many shapes and sizes. Safe and cost effective tank waste retrieval and closure operations are challenging. In order to meet the challenges associated with the tank cleanup activities, more effective technologies are needed. Previous water-sluicing and pumping campaigns have been effective for tank liquid and bulk sludge removal, but are not always effective at meeting the final cleaning requirements necessary to close these large underground waste storage tanks.

The DOE Office of Science and Technology (OST), in cooperation with the DOE Environmental Management (EM) Program, funded the development of a remotely operated vehicle named Houdini® to help meet final tank closure requirements. RedZone Robotics Inc, a small company in Pittsburgh, Pennsylvania, designed the Houdini® System, which was originally developed through the OST Industry Research and Development Program at the National Energy Technology Laboratory (NETL), located in Morgantown, West Virginia. The OST Robotics Crosscutting Program, the Ohio Field Office- Fernald EM Program, and the Oak Ridge Operations EM Program provided technical oversight and end-user feedback. Initially intended for use in the K-65 Silos at the Fernald site in Southwestern Ohio, the Houdini® was redirected to the Gunite Tanks Remediation Project at Oak Ridge National Laboratory (ORNL), located in Oak Ridge, Tennessee, where it was more urgently needed.

The Houdini®-I system was successfully deployed at ORNL during the Gunite Tanks Remediation Project, from June 1997 through August 1998, in tanks W-3, W-4, and W-6. Lessons-learned from these operations made it apparent that improvements could be made on a second-generation system. This paper summarizes major improvements included on the Houdini®-II system, and describes its performance and maintenance during the final four waste removal campaigns for the ORNL Gunite and Tanks Remediation Project.

THE HOUDINI®-II REMOTELY OPERATED VEHICLE SYSTEM

The Houdini®-II is a hydraulically powered, remotely operated vehicle that provides important functions for tank waste removal operations. The vehicle's 4-ft by 5-ft parallelogram style frame folds, enabling it to deploy through 24-inch tank riser openings. The Houdini®-II is equipped with a front plow blade, a dexterous, high-payload, Schilling Titan III manipulator arm, and a remotely operated, dual camera system. The Operator Control Console can be located a few hundred feet away from the vehicle. The Power Distribution And Control Unit (PDCU) provides pressurized fluids to both the Tether Management and Deployment System (TMADS) and to the vehicle (via a tether) to meet the high-power density requirements of the Houdini® system's hydraulic functions. The hydraulic servo valves provide the operator with variable speed control for all vehicle and deployment system operations. The Houdini®-II consists of five main sub-systems (Fig. 1).

(Fig.1) The Houdini® system components include the vehicle, tether, tether management and deployment system (TMADS), the power distribution and control unit (PDCU), the control console, and the optional suitcase controller as seen by this RedZone diagram.

The Houdini® Vehicle

The Houdini® vehicle is a tethered, hydraulically powered, track-driven, remotely operated, “bulldozer type vehicle” that is the "work horse" of the Radioactive Tank Cleaning System for the Gunite Tanks Remediation Project (Fig. 2). The collapsible, parallelogram, stainless-steel frame folds to enable entry into cylindrical tank risers with diameters as small as 24-in. The frame fully expands to a footprint that is about 4-ft wide and 5-ft long that provides a stable platform for a variety of in-tank operations. The stainless steel construction of the Houdini® vehicle makes it well suited for corrosive and high pH environments.

(Fig. 2) The Houdini® is a tracked vehicle equipped with a plow blade, robotic manipulator arm, dual camera system, and lights as seen in this RedZone photo.

The vehicle is equipped with a squeegee-tipped plow blade and is hydraulically actuated from the Operator Control Console to perform tank waste retrieval operations. The onboard, remote, dual camera system has a variety of functions to fully service the viewing needs of the operator. The vehicle is also equipped with a 6-degree of freedom, Schilling Titan-III manipulator arm with a payload capacity of 250-lb and a full reach of about 5-ft.

The Tether Management and Deployment System (TMADS)

The TMADS is the mobile enclosure that provides the containment and housing for the Houdini® vehicle before, during, and after deployments into the tank. The enclosure supports tank deployments and maintenance services to the vehicle. The TMADS consists of three main compartments (Fig. 3) that are described below.

The Tether Reel Compartment is the top section of the TMADS assembly. The 4-ft diameter tether reel is hydraulically powered and provides variable speed tether management for tank deployments and operations. It provides up to 3,000-lbs of lifting force for vehicle retrieval. The Tether Reel Compartment also contains the control valves and redundant, fail-safe, braking interlocks to ensure safe operation of the tether reel. The control valves for the tether reel drive are located inside a removable access panel in the front face of the compartment where it can be easily serviced.

The Robot Compartment stores the Houdini® vehicle when not deployed into the tank. The compartment has 4-ft by 8-ft front and rear panels, fabricated from a transparent polycarbonate material to provide a clear view of the vehicle during storage and maintenance activities. Gloveports installed in the front and rear panels and a pass-through box support routine maintenance activities without breaking containment, and a safety chain secures the vehicle to prevent unwanted movement during maintenance activities.

The Containment Bezel is in the lowest compartment of the TMADS structure and attaches directly to the main containment door that isolates and shields the interior of the TMADS from the tank. The containment door opens remotely during deployment and allows the vehicle to enter the tank. The Containment Bezel provides mating flanges for adapting other support systems like a Tether Handling System to support other tooling needs. A 20-in bag-out port was installed in the Containment Bezel, allowing larger items to be inserted or bagged out of the TMADS.

The Tether

The Houdini® vehicle is powered by the tether, which is a multiconductor cable with integrated hydraulic transmission lines. One end of the tether attaches to the vehicle, while the other end is attached to the tether reel inside the TMADS. The tether supplies the vehicle with both hydraulic and electrical power. The tether is approximately 3-in in diameter, with a length of 135-ft. Kevlar material inside the tether provides up to 10,000-lbs of tensile strength for deploying and retracting the vehicle in and out of the tanks.

The Power Distribution and Control Unit (PDCU)

The PDCU enclosure consists of an insulated, weather resistant structure that contains the electrical switch gear, hydraulic power supply, and electronic power supply needed to operate the Houdini® system. The interconnecting cables for the PDCU allow the unit to be positioned up to 100-ft from the TMADS. Access doors on each of the unit's four sides provide entry into the PDCU for maintenance and trouble shooting operations. Centrally located on the exterior of the PDCU are the quick connections for the electrical, hydraulic, water, and air supplies.

The Operator Control Console

The Operator Control Console is directly hard wired to the PDCU and provides total control and monitoring for all remote vehicle functions. The console may be located up to 300-ft away from the PDCU. The console contains two joysticks, camera monitors, and a remote control master arm and controller for the vehicle's robotic arm (Fig. 4). The relative positions of the joystick independently control the speed and direction of each track on the vehicle, simplifying the vehicle's controllability. Warning lights and alarms on the console alert the operator of abnormal conditions, while individual switches control the camera views, tether feed, plow position, and frame folding functions.

SYSTEM COLD TESTING AND REDESIGN MODIFICATIONS

The Houdini®-II system arrived at ORNL in September 1998 with some uncompleted items. Because of schedule and budget overruns, the final integration of the Houdini®-II system and the systems' acceptance testing (originally scheduled at the vendors' facility) were performed at the ORNL Tanks Technology Cold Test Facility. The initial cold test environment was debris free and dry. The primary objective during the initial testing and integration was to operate the system without introducing it into demanding environments. A few potential deficiencies required modification to meet the overall system requirements in the first week of the cold tests.

A major identified problem was the TMADS containment structure's inability to be easily attached to and detached from the tank risers. The process used for the Houdini®-I system required making and breaking the riser extension piece located on the lower side of the Containment Bezel at platform level (Fig. 5 – left side). The TMADS assembly had to be disconnected from the riser extension and sheet metal caps had to be installed to seal the opposing flanges to prevent the spread of contamination. The original TMADS design on the Houdini®-II system had even more of an offset and complicated the disconnection process even more. The TMADS was modified so that it could be separated at the base of the robot compartment (Fig. 5 – right side). Special contamination plates were designed and fabricated to seal off the opposing contaminated openings.

It was also noted that the TMADS would not easily mate with the maintenance tent in the South Tank Farm due to the height of the TMADS Robot Compartment maintenance doors, which were originally designed with a continuously hinged vertical door on each side of compartment. Safety and health physics personnel identified these doors as potential contamination traps that were virtually impossible to thoroughly clean. Modifications were discussed with safety and health personnel to improve contamination control. One door was completely removed and replaced by a one-piece panel with a continuous neoprene gasket that totally seals the area. The other fully hinged vertical door was removed and replaced with a bottom-hinged door that has a dual purpose. First, this door provides containment for the compartment, and second, it functions as a ramp aiding in the removal of the vehicle to the maintenance tent.

TMADS Containment Bezel Modifications

The Containment Bezel is found in the lower section of the TMADS. In the initial TMADS design, access into the Containment Bezel was limited, which made it difficult to perform minor maintenance to the gripper/wrist segment on the vehicle's Schilling arm using the vendor supplied glove ports. In addition, these glove ports would not reach and support the added 20-in bag-out port located in the Containment Bezel assembly. Modifications implemented at ORNL to reduce these limitations included the installation of two additional glove ports and viewing windows into the Containment Bezel assembly next to the 20-in bag-out port.

Cold tests were completed on the Houdini®-II system in early December 1998, and the acceptance testing and readiness review were successfully completed by the end of December 1998. The system was ready to provide important waste removal operations in the large, 50-ft diameter, 170,000-gallon gunite tanks located in the South Tank Farm at ORNL.

HOUDINI®-II OPERATIONS IN THE GUNITE TANKS

Tank W-7 Operations

The Houdini®-II system was moved and installed on the tank W-7 equipment platform, and then powered up and checked out on January 26, 1999. The vehicle was deployed and retracted on January 28, 1999 for final procedure and system verification. The Houdini®-II system began full-scale operations on January 29, 1999, and operated for approximately 80 hours over the next 6 weeks. The vehicle speeded up waste removal operations as it plowed sludge toward the Confined Sluicing End-Effector deployed in the tank by the Modified Light Duty Utility Arm. The vehicle's robotic arm was used to pickup debris and move it to a consolidation area for removal out of the tank. The robotic arm also took waste samples and deployed the coring tool, successfully taking 5 core samples from the tank walls.

Minor hardware failures identified during waste removal operations in tank W-7 were successfully repaired while the vehicle was stowed in the TMADS. The tilt-down function of the vehicle's body camera was lost during the first full day of operation; however, the effect of this failure on plowing operations was negligible. Hydraulic leaks were identified on the Shilling arm, the plow cylinder, and on both the left and right track drive motors over the course of the 6 week operations period. The manifold plugs and frame bolts were found to periodically loosen, but were regularly inspected and tightened.

On March 10, 1999 the wrist rotate and gripper open/close functions failed on the Titan III Shilling arm. In addition, the arm developed severe spasms whenever the manipulator hydraulics was powered up. The vehicle continued to be used for plowing operations since waste removal operations were nearly complete in tank W-7, but the arm was positioned out of the plow’s way and then “frozen” in place. Plowing operations were completed on March 13, 1999. After the tank W-7 waste removal campaign, several weeks were spent trouble shooting the arm malfunction(s), with some assistance from the Alstom Automation/Schilling Robotics Corporation. The root cause was traced to the tether termination on the vehicle. Water had leaked into the termination canister and caused several wires in the Schilling arm controller cable to short out and burn. Investigation of the tether termination revealed a split in the flexible bend restrictor, which was concluded to be the entry point for the water. Repair of the contaminated tether was impractical, so a new tether was purchased from RedZone Robotics, Inc. The tether was successfully installed on the Houdini®-II system in the maintenance tent at the South Tank Farm in early September. The system underwent a short burn-in period (run time) while awaiting the next scheduled tank deployment.

Tank W-10 Operations

The Houdini®-II system was moved to tank W-10 in October 1999, and powered up and deployed into the tank on October 14, 1999. During the next week, the system logged over 30 hours of in-tank operations without any major delays. During the 30 hours of operations, the vehicle was deployed and retracted 3 times and was used to deploy the Confined Sluicing End-effector (CSEE) and the coring tool. The vehicle effectively picked up and consolidated debris in the tank, and plowed sludge to the CSEE.

Minor problems were encountered during tank W-10 operations. They consisted of a hydraulic leak from a loose plug in the track manifold, which was repaired within 2 hours, and an electrical problem with the manipulator’s communication cable that became unmanageable during the attempt to take the last core sample in the tank. After completing waste removal operations in tank W-10 in late October, the Houdini®-II system underwent additional troubleshooting and repair for the Schilling arm electrical problems. This time the problem was traced to a cold solder joint that caused inconsistent communications between the arm and its slave controller unit. The Houdini®-II underwent a connector change-out on the Schilling communication cable to fix the problem.

Tank W-8 Operations

The Houdini®-II system was installed on tank W-8 and the vehicle was deployed into the tank on January 11, 2000. Over the next 3 months the Houdini®-II system supported confined sluicing and tank cleaning operations. In addition to its normal in-tank activities, the vehicle deployed a newly designed wall-washing tool (the Linear Scarifying End-Effector) and eliminated undo strain on the Modified Light Duty Utility Arm, which was suffering from its own tether problems. The Houdini®-II system logged over 75 hours of operations in tank W-8. During these operations, the Houdini®-II system was deployed and retracted 4 times, made 10 hand-offs of the CSEE to the MLDUA, 8 hand-offs of the Linear Scarifying End-Effector (LSEE), 12 hand-offs of the coring tool, and also picked up debris in the tanks and plowed sludge to and from the CSEE in the grasp of the MLDUA.

One minor problem was encountered during operations in tank W-8 and was identified as a hydraulic leak from a loose plug in the track manifold. This repetitive problem was identified as a design flaw and a permanent fix is on the horizon. Due to schedule and budget pressures, the correction will be implemented after completing waste activities in the gunite tanks.

Tank W-9 Operations

The Houdini®-II system was installed on the south riser of tank W-9 in August 2000 and was powered up over the normal 2 to 3 day period. Because tank W-9 was the designated consolidation tank for all sluicing activities for the Gunite Tanks Remediation Project, the sludge levels were higher than normal. The Houdini®-II vehicle successfully performed plowing activities with sludge levels as high as 28-in., leveling and mixing all the sludge piles into the residual tank liquid, making a slurry that was removed by the Confined Sluicing End-Effector. The Houdini®-II system logged over 80 hours of operations in tank W-9, and spent a total of 9 days performing plowing and debris removal activities. In addition, the vehicle was deployed and retracted 6 times, deployed and made 5 handoffs of the Confined Sluicing End-Effector and Linear Scarifying End-Effector, and performed wall washing, wall coring, and sludge sampling operations.

During operations in tank W-9, the Houdini® vehicle suffered another problem with a manifold plug and had to be retracted into the TMADS for repair. During the repair of the right manifold plug, a bungee cord was found wrapped around the track idler sprocket. The vehicle was repaired and deployed in the tank within a few hours.

LESSONS LEARNED

Houdini® Performance Items

TMADS

The current design of the Houdini®-II TMADS has greatly improved over the Houdini®-I prototype design but still needs additional improvements to the system ergonomics. The maintenance doors on the narrow sides of the TMADS had full-length hinges and did not seal very well. New doors with positive compressive seals were used and all full-length hinges where removed. Only one side of the TMADS was equipped with a maintenance door and the other side has a continuous panel bolted firmly in place. The maintenance door side was reduced in size and hinged along the bottom edge to create a ramp to facilitate easier removal of the vehicle into the maintenance tent.

The current design of the TMADS provided lights and cameras inside the robot compartment of the TMADS to monitor critical operations or maintenance and repair activities. A separate power supply could make these assets more versatile. Current OSHA safety regulations (Lockout/Tag out) requires a lockout of the system power during maintenance and repairs. This prevents the use of the cameras and lights until power can be restored. Currently, a droplight installed thru a glove port would provide the necessary light to conduct maintenance and repair activities. In additions to the lights and cameras, the TMADS Hoist is a very important support system inside the TMADS containment structure. The hoist should also have a separate supply and all of these supplies need to be accessible on the outside of the containment structure. The hoist should have only a local control for safe operations.

The Houdini®-II TMADS was equipped with a 20” bag out port similar to the Houdini®-I TMADS. The port was located in the containment bezel in the lower section of the TMADS. When the decontamination spray ring (DSR) was activated, water spray and splash made sealing of the 20” bag-out port very difficult. Over night seepage would always require next day cleaning therefore the port was sealed with a transparent polycarbonate material window for additional light in the Containment Bezel.

The glove port access into the Containment Bezel is limited. The Houdini®-II containment bezel design only has access on three of the four sides. This along with the extended reach caused by the extended sides for mating the Tether Handling System (THS) makes the reach to the vehicle very difficult. Increasing glove access and reducing reach makes maintenance to the vehicle more manageable. Modifications made to the TMADS and containment bezel during the cold testing of the Houdini®-II system have minimized these limitations and problems.

The addition of a double door pass-thru box on the Houdini®-II TMADS improved the maintenance needs. The redundant double door pass-thru boxes of the same size on the TMADS provided minimal benefits. For larger items a larger double door pass thru chamber would support the addition of larger items into the TMADS for operations and maintenance.

Due to the regular maintenance requirements of the vehicle, the TMADS was required to function as the work area for the vehicle. The wider robot compartment provided the additional space to allow for opening of the Houdini® vehicle to access critical areas of the vehicle for maintenance. Tool trays and the addition of special tooling supported a variety of maintenance and repair activities of the vehicle.

Vehicle

Water glycol hydraulic fluid used in the hydraulic systems was found to cause a number of problems on Houdini®-I for both the Schilling Arm and the vehicle's hydraulic components.

The lugs on the vehicle tracks produced more vibrations than anticipated. Conventional locking methods used for bolts and other fasteners have been ineffective at preventing them from becoming loose. New and creative methods have proven to be successful at eliminating the loosening effects of the vibrations.

Changes to the hydraulic plumbing on the vehicle have eliminated hoses, that in the past have become loose and caused leaks during operations. The new hose and cable routing, with the addition of the internal hydraulic passageways eliminated hoses from becoming loose or damaged when the vehicle frame was opened and closed.

Redesigning camera mounts with smaller and more compact cameras in conjunction with the change in the vehicle's center of gravity, have eliminated damage during deployments and retractions. Changing the center of gravity of the vehicle to hang straight during deployments and retractions reduced riser interferences and self inflicted damage to the vehicle. The onboard vehicle camera experienced problems with the pan and tilt unit. The camera pan and tilt units frequently became stuck and wouldn't move. Stronger pan and tilt drives would prevent this from continuing to be a problem.

Increased travel on the track adjustments has made track changes a relatively painless activity while the vehicle is hanging in the TMADS. The previous design made track changes very difficult and required removing track drive sprockets to compensate for limited track adjustment travel.

The relocation and integration of the vehicle position limit switches and other sensing technologies into the enclosed sections of the vehicle manifolds have made the operation of the limit switches more reliable and less prone to damage.

The slower traverse speeds (1 Ft/s) of the Houdini®-II vehicle have made it easier to control than the first version's (2 Ft/s) and less prone to self inflicted damage.

Schilling Arm

One of the redesigns on the Houdini®-I system was to remove the Schilling Arm Slave Controller Box from the vehicle and relocate it inside the Tether Drum in the TMADS. This was done because of the radiation-sensitive electronics contained inside the Slave Arm Controller Box. These electronics would not take the higher levels of radiation dose over extended periods of time. The Slave Arm Controller Box was accessible through an access hatch located on the side of the Tether Reel Compartment in the upper section of the TMADS. The down side of this improvement was all the individual communications lines between the slave arm and the slave controller had to pass down through the 135 feet vehicle tether to the arm. This in conjunction with some earlier failures of the vehicles tether caused severe problems with the functionality of the Schilling Arm on the Houdini®-II system and led to a complete replacement of the tether.

The Schilling Arm is a very powerful manipulator capable of delivering lifting forces in excess of 200 pounds. This amount of power can easily damage a variety of things in the tanks and on the vehicle itself. Because of this power, operators had to possess a great deal of skill to carefully manipulate in and around other equipment and debris. Even the best operators occasional bump into things. Force feedback on this type of equipment would help to prevent delivering excess force to delicate objects.

The housing of the original Schilling Titan II Arm contained a captive cavity under the shoulder joint where sludge accumulated during operations. These accumulations of sludge were resistant to decontamination operations and could only be removed by disassembling the arm. The Titan II was replaced with a Titan III that had a sealed cavity.

The manifold mount modular style design of the gripper camera on the Houdini®-II Schilling Arm created a leak path into the arm. Any damage that occurred to the camera housing or glass lens would allow water and sludge to find its' way into the arm. The location of this camera is very critical to give the best view. Unfortunately, locating the camera near the gripper end of the arm made it prone to collision when trying to manipulate the grippers onto an object. The wide-angle lens on the gripper camera gave a very detailed one-dimensional view of the gripper.

The Schilling Arm relief valve that prevents the build up of internal housing pressures was easily damaged during vehicle retractions. Damage to the relief valve allows water, sludge and debris to enter the arm and drastically affect its performance. Visual inspections after retractions of the vehicle into TMADS were crucial to determine if any damage occurred. Changes in the center of gravity of the 2nd generation Houdini® vehicle eliminated this problem.

Tether

All hoses, connectors and cables on the Houdini® vehicle were prone to damage during operations in the harsh tank environments. The electrical cables and hoses that were damaged on the Houdini®-I vehicle during deployments and retractions were very difficult and time consuming to change. These cables and hoses had to be spliced and/or soldered inside the TMADS robot compartment to be repaired. Repairing the cables, hoses and connectors in the TMADS were a very tedious and difficult operation. Redesigns to the tether termination made it possible to disconnect and replace the entire hose or cable thereby significantly reducing repair/down-time of the equipment. The new tether design on the Houdini®-II system with connectorized vehicle termination end has proven to be very field serviceable. The connectorized vehicle termination allowed for easy replacement of damaged cables, hoses and connectors on the vehicle without re-soldering the electrical connections.

The unforeseen problem associated with the new tether termination design was a catastrophic failure suffered in the initial deployment in tank W-7. The wedging and gripping action of the termination to the tether slipped causing the bend restrictor to crack and leak water into the termination. The water then shorted the wiring and totally shut down the operation of the Schilling Arm. In order to correct the problem, a new tether was purchased from the vendor and installed on the system. Future designs could not only provide a serviceable termination, but also waterproof potting on the back shell of all connectors to improve the resistance to moisture.

Houdini®-Maintenance Items

Although the maintenance tent has been an extremely helpful tool at the ORNL tank farm for the Houdini®-maintenance, it has also been cost and schedule prohibitive at times. The setup, connection and disconnect of the equipment to the tent raise some moderate costs and schedule delays that really impact the productivity of the equipment. The maintenance tent or major systems could be designed for quicker connection and disconnection.

Maintaining tolerable working conditions in the maintenance tent during the summer months has proven to be very challenging. The heat load from the sun during the summer makes the containment area of the tent very uncomfortable. Heat stress limitations affect the duration of the work activities.

Designing the containment structures of the equipment, i.e. TMADS, by qualified and experienced personnel to handle a variety of maintenance activities has proven to be cost effective at minimizing unnecessary costs and schedule delays.

CONCLUSION

The Houdini® -II system made only one trip to the maintenance tent during scheduled operations in the final four tank cleaning campaigns to replace the catastrophic failure of the tether shortly after it's first deployment in tank W-7. All other repairs were performed in the robot compartment of the TMADS. The vehicle experienced a few hydraulic leaks, with the Schilling arm accounting for most of the leaks during operations in tanks W-7 and W-10, and the track motors and track manifold plug accounting for the leaks during operations in tanks W-8 and W-9. A repair was made to a faulty relief valve in the hydraulic return side of the Schilling arm. This was a challenging repair due to the TMADS limited access when working on certain parts of the vehicle.

Bearings on the drive motor, especially the left rear one under the tether termination, seem prone for frequent failures. Early in the operations in tank W-7, a low hydraulic reservoir alarm warned the operator of a possible hydraulic leak. It was later determined that the shaft seal in the left side hydraulic track drive motor was leaking. After removing and replacing the drive motor, the leaky seal was attributed to a badly worn bearing. Other bearing materials are now being tested, and have out lasted the old bearing material almost three times longer.

The Houdini®-II system successfully performed challenging waste removal operations during the final four waste removal campaigns of the Gunite Tanks Remediation Project. The overall satisfaction with the modified system is high. Both of the Houdini® remotely operated vehicle systems were used as "mini bulldozers" to push sludge toward the confined sluicing intake. The vehicle's robotic arm was extremely valuable for its tool handling and grasping skills, and was successfully used for waste sampling, core sampling, debris consolidation, and waste removal operations. Although both Houdini®-I and Houdini®-II experienced a variety of component failures, the Houdini®-II is clearly an improvement over the Houdini®-I in reliability and accessibility for maintenance and repairs. The maintainability and reliability of the Houdini®-II system has increased considerably over its Houdini®-I counterpart. Most repairs on the Houdini®-II system were directly associated with the harsh environment in which it was required to operate. When working in harsh environments, these types of repairs should be expected and factored into regularly scheduled maintenance. Both of the Houdini® remotely operated vehicles were important to successful waste removal operations in 7 large underground waste storage tanks conducted during the Gunite Tanks Remediation Project at ORNL.